30 June 1967

RSIC-679

FACILITIES FOR SIMULATING ATTITUDE MOTION OF SPACECRAFT

by

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ABSTRACT

This report describes facilities using gas bearings in attitude motion simulators for the development of spacecraft attitude control systems. Typical facility information includes discussions on test chamber, bearing, platform, power requirements, balance consideration, testing procedure, attitude reference sources, sensors, and data transmission. Facilities at twelve Government and industrial organizations are discussed.

FOREWORD

This survey of attitude motion facilities employing gas bearing supported platforms was made at the request of the Guidance and Control Division, Astrionics Laboratory, Marshall Space Flight Center, Huntsville, Alabama.

The primary sources searched for information are as follows:

1) Redstone Scientific Information Center Document Card File.

2) Defense Documentation Center Abstract Bulletins and Bibliographic Service.

3) National Aeronautics and Space Administration tape search which references International Aerospace Abstracts and Scientific Technical Aerospace Reports.

4) Astronomical and Scientific Publications.

Also, written requests for information on existing and planned facilities were sent to thirty-one Government and private organizations, including foreign enterprises. Seven positive answers were received, all from private industry within the United States.

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ILLUSTRATIONS

I. INTRODUCTION

Attitude motion simulators are used for development and qualification testing of components and complete systems of spacecraft attitude control systems.[1] A simulation system consists of rate and position sensing devices, torque producing devices which maintain the desired attitude, and the necessary electrical, electronic, and telemetry equipment for collecting and reporting data. An attitude control system performs three basic tasks in flight: attitude acquisition, steady-state control, and maneuvering. The attitude motion of a space satellite can be described as the rotational motion about its center of mass.[2] The attitude of a space vehicle refers to its orientation as determined by the relationship between its axes and some reference line or set of axes.

Items such as the sensors, computers, telemetry, torque-producing systems and ground support equipment may be tested.[3,4,5] Facilities may be used to simulate the manual control characteristics of manned reentry bodies.[6] It is usually desirable but very difficult to test the systems' dynamic performance near the true space environment.

The development of more advanced space programs involving great distances from the Earth dictates more accurate guidance and control systems which require improved simulating techniques.[1] Simulation of the in-flight performance of an attitude control system could entail duplicating in the earth's gravity field the frictionless state of a body in free fall in orbit. This is accomplished by installing the system in the desired simulator vehicle which is attached to a spherical gas bearing.[7] A spherical gas bearing is chosen to support the simulator vehicle because of its capability to simulate frictionless suspension and almost unrestricted freedom of angular motion in three axes.[8,9]

The design of a simulator is determined by the requirements of a particular spacecraft attitude control system.[10] However, some simulators are versatile and can be used for a variety of control systems and several vehicle sizes. Some of the most important considerations in the design of an attitude motion simulator are:[9,11,12,13]

1) Vehicle weight and moments of inertia.
2) Bearing size, gas, and gas pressure.
3) Test chamber size, vacuum or air conditioned, temperature control.
4) Seismic isolation of the pad.
5) Platform balancing.
6) Sources of unbalance torques.
7) Attitude control sensors, computers, and torque-producing components.
8) Reference sources to be simulated.

9) Measurement and control accuracy.
10) Platform power.
11) Data transmission - from the platform to the control center.

II. SPACECRAFT MOTION AND SIMULATION

Few space missions can be accomplished without controlling the motion of the craft.[2] Instrumented space satellites may require that antennas be pointed to transmit data back to earth or that solar panels be oriented to receive maximum solar radiation. Thrust vectors must be precisely oriented to make trajectory corrections in flight, to put vehicles into orbit or to reenter the earth's atmosphere. It may be necessary that an earth satellite keep one axis aligned with the gravity vector in order that the surface or cloud cover be scanned. Some test facilities may be required to simulate any of these maneuvers and have an operating and measurement resolution of less than 1 arc-sec.[1] If a spacecraft, journeying from the earth to the sun, had a heading error of 1 arc-sec, it would be approximately 450 mi off course when it reached the sun.

One facility is used to test a control system which points an experimental package toward the sun and stellar targets and stabilizes each axis within +20 arc-sec.[16] This facility is also used in the testing of ground support equipment. A three-axis reorientable momentum-wheel controller is currently undergoing tests in one facility which was built to be used in the development of a 5500-lb earth-orbiting vehicle 30 ft long.

Time-varying disturbance torques may be simulated by magnetic torquing of the air-bearing supported platform. In one facility the magnetic field profile is generated by programing Helmholtz coil currents as time functions using analog curve followers. In another a magnetic torquing system for satellite attitude orientation was tested in an air-bearing facility.[17] A scaled-up artificial magnetic environment field was generated by a set of three orthogonal coils 12 ft in diameter placed around the platform.

III. BEARINGS

The gas bearing may be required to support several thousand lb and produce turbine and friction torques below 100 dynes-cm.[15] For this reason, sphericity and finish tolerance are in the order of millionths of an inch.[9, 10]

The bearing must allow unrestricted angular motion about three axes and produce frictionless suspension and mutual equilibrium at any deflection angle.[18] The air-bearing base supports the air-bearing cup or socket and a mechanism which supports the ball when the air pressure is off.

The balls used in air-bearing motion simulators vary from 3 to 22 in. in diameter and support loads from 30 to 16,000 lb using air or nitrogen at pressures ranging from 6 to 300 psi. The ball displacement may vary from one to several thousandths of an inch, and the gas consumption may vary from 0.5 to 20 scfm.

The number of orifices in the bearing cup may vary from 1 to 40. One facility uses a ring of ruby watch-jewel orifices.[19] The majority of the balls used are made of stainless steel or hard aluminum. Bearing disturbance torques are listed from 3 to 10,000 dynes-cm. The bearings are usually allowed 360 deg motion about one axis from 30 to 120 deg about the other two.

IV. SEISMIC FOUNDATION

In order to take full advantage of the capabilities of the spherical air bearing, it is necessary to eliminate seismic disturbances. This has been done by mounting the simulator on a seismic slab which is supported by springs. The Boeing Company used seven air springs to support a 90,000-lb concrete slab.[19] Three master springs provided constant height support and were equipped with level-sensing valves which shuttle pressurized air to and from the four remaining springs to maintain the slab parallel to its base. Less than 100-μ in. slab motion was obtained.

Grumman has a 215,000-lb seismic slab which is mounted on twelve coil springs. Both foundations reduce the seismic disturbances to a level which can be tolerated by the precise attitude controls.

V. BALANCE CONSIDERATIONS

After the initial disturbance of the simulator vehicle, control torques initiated by the attitude control system produce any desired change in vehicular motion. Besides control torques, undesirable torques due to friction and unbalance can alter vehicular motion. Techniques to eliminate these unbalanced torques are of great importance in the design of attitude motion simulators.[9,18]

Earth-based duplication of the dynamic performance characteristics of attitude control systems gives rise to extraneous torques which adversely affect the simulation procedure. These can be categorized as torques resulting from three causes: the earth's gravity acting upon the displacement of the center of mass from the center of rotation, turbine torque produced by an air bearing, and environmental factors which include seismic vibration, air movement, air resistance, and magnetic effects.

Elimination of platform deformation must also be considered in the design of a platform. Mass shift, which may result from platform anisoelasticity, movement of equipment aboard the platform, unsymmetrical propellant depletion and discharging of batteries, must be reduced to a minimum.[19] Automatic feedback leveling systems may be used for very accurate platform leveling.

Platforms may be made of materials which are very rigid and do not deform at wide-angle maneuvers or with temperature change. The movement of equipment is minimized by fastening everything rigidly to the platform. Any nonrigid members such as wires are made rigid or are balanced so that their movement will not affect the center of rotation to any significant degree. Gas used in control jets is stored in bottles arranged symmetrically about the center of rotation and are depleted simultaneously. Thermal gradients in platform are introduced by local heating of equipment or by simulated stellar sources and convection currents. Boeing minimizes the thermal shift by using all aluminum or magnesium structures which allow the heat to spread rapidly, equalizing the temperature of the simulator. This equilibrium is obtained during a 1-hr warm-up period. Heat effects from the sun source are minimized by placing the sun source outside their temperature-controlled room.

VI. SIMULATION OF SOURCES AND SENSORS

Some of the solar simulators consist of the following light sources:[1,11,16,17,19]

1) A 500-w lamp
2) Four flood lights directed through a Fresnel lens
3) Eighteen water-cooled Xenon 6-w arc lamps
4) Sixteen lamps powered by rectified three-phase A-C and drawing 87 amp at 112 VDC. Also, 256 parabolic reflectors are grouped with individually adjustable lamps at their focal points. A $\frac{1}{2}$-in. honeycomb 4 in. thick eliminates the stray light from the reflectors and provides a beam collimated to approximately 4 deg.[19]

5) A 300-w zirconium arc lamp and a 7-in. projection lens adjusted to give collimation of $\frac{1}{2}$ deg.[19]

One star simulator consists of a reflecting telescope 6 in. in diameter with the light source located at the focal point of the mirror. This places the star at infinity for collimation of the light. A difficulty with this type of star simulation is the proper alignment of the star sensor and the simulator. The intensity of the lamp is controlled by an independent power source and is adjusted to the proper intensity to resemble the desired star magnitude. Another simulator is a Sylvania glow modulator tube, R1131C.[16] In still another simulator five collimators, 15 in. in diameter, located within the vacuum chamber, provide stellar simulation. Each provides a star whose angular subtense is less than 8 arc-sec with a parallax error of less than 5 arc-sec. The output of each unit may be varied to represent stars of from -1.0 to +6.0 magnitude.

The sensors utilized in spacecraft are largely inertial, but may be of various types such as heat, horizon, gravitational vector sensing devices, or celestial body seekers. Those used on the simulators are usually actual flight sensors.

One sun sensor consists of a shadow-cast aperture which changes the area of sunlight that falls on an array of photovoltaic silicon solar cells as a function of the angle of the sun line.[16] An XY20D micro-system radiation tracking transducer is used as a star tracker.

VII. THE BOEING COMPANY: PRECISION AIR-BEARING SIMULATOR AND TEST FACILITY*[19]

A. Design

The Precision Air Bearing Simulation and Test Facility (PABST) consists of several platforms:

1) Satellite Attitude Control Simulator (SACS)
2) Spinning Space Station (S^3) platform
3) High Accuracy platform
4) Burner II air bearing simulation (Actual spacecraft mounted on spherical air bearing)

In addition to the air-bearing platforms listed above, Boeing has an air-bearing mounted moving-base cockpit for study of manned space rendezvous and docking. Table I lists design parameters of these platforms.

*Seattle, Washington.

Table I. Parameters of Boeing Air-Bearing Simulation and Test Facilities

Parameter	Axis	Air-Bearing Platform				
		SACS	S^3	High Accuracy	Docking Simulator	Burner II
Degrees of freedom		3	3	3	3 + 3	3
Angular freedom (deg)	X	±360n	±360n	±360n	±720	±1080
	Y	±105	±30-70	±40	±40	±65
	Z	±105	±30-70	±45	±40	±65
Minimum moments of inertia (slug/ft^2)	X	100	14	40		33
	Y	80	12	26		77
	Z	80	12	26		80
Maximum moments of inertia (slug/ft^2)	X	500	200	100		79
	Y	400	165	80		140
	Z	400	165	80		144
Tare weight (lb)		1400	300-650	550	1100	700
Payload capability (lb)		800	700	700	900	
Bearing type		M. O.*	M. O. with feed-thru	M. O.	M. O.	M. O. step

*Multiple orifice

Table I. Parameters of Boeing Air-Bearing Simulation and Test Facilities (Concluded)

Parameter	Air-Bearing Platform				
	SACS	S^3	High Accuracy	Docking Simulator	Burner II
Ball diameter (in.) and material	12 Stainless steel	10 Aluminum hard-coated	10 Aluminum hard-coated	6 Aluminum hard-coated	8 Aluminum
Bearing turbine torque (g/cm)	3	10	1.0	-	-
On-board power (kwh)	1.8	1.5	1.8	-	Mission hardware
Telemetry	8-Channel PDM	12-Channel FM-FM	12-Channel FM-FM	Cable	Cable
Altitude chamber operation	No	No	No	No	Yes
Bearing gas consumption (scfh)	0.5	0.7	0.5		

The building in which the facility is located was built upon friction piling. The ground under a large portion of the building is sand fill. This type of foundation construction is poor for minimization of floor vibration. The dominant frequency of the disturbance is three to five cycles and is, therefore, difficult to isolate. (A large number of seismographic measurements were taken in various areas of the building to find locations of low noise, but this effort was met with no success.) The desired result was to have a facility floor with horizontal and vertical vibration amplitudes of less than 100 μ in. This amplitude was chosen to give a 1-to-10 factor between amplitude of vibration and nominal air-bearing film thickness.

In the facility design two areas received prime consideration: disturbances and provision for a celestial reference. The disturbances considered were seismic vibration, room air currents, and turbine-torques created by gas flow from the air bearing. The celestial references required were a sun simulation which allowed acquisition and limit cycle, and a star simulation. These references were to be satisfactory for use with spacecraft-type hardware and were not to conflict with the other requirements of the facility. The dimensions of the facility had to be compatible with the design of mounting an entire space craft with solar panels extended.

During wide-angle maneuvers and after the initial sun acquisition, disturbances are introduced by the bending of the platform structure and the movement of the equipment thereon. The problem of movement of equipment is minimized by taking very deliberate care to fasten everything down on the platform very tightly before operation is attempted. This tight fastening must, in fact, include all wiring and other small addenda as well as the obvious heavy equipment.

The structural compliance is a problem that must be considered in the design of the platform. Torques arising from the unbalance due to compliance must be considerably less than the control torque capability to allow testing of the vehicle performance at positions or attitudes away from the static null.

Mass shift caused by thermal gradients of the platform must also be controlled. During operation of the simulator, the heat that the control system and related hardware generates may cause a thermally induced mass shift within the platform; this shift in equilibrium must be minimized when laying out the platform.

The celestial references pose a problem in their operation which conflicts with the minimum air current requirement. This conflict arises because the lamps used to simulate a wide-angle sun produce heat and require forced ventilation for heat removal. The design must introduce a minimum of air currents and simultaneously allow the platform to acquire the sun from any random condition.

The intensity and beam width of the light beam representing a star must allow the star tracker to operate throughout the simulator limit cycle range. The sun source is made in two distinct sections. One has a very large area to accommodate initial acquisition, and the other is smaller for small-angle operations. The collimation requirements of the large source are not as stringent as those of the small source because acquisition is not dependent on a highly accurate sensor output.

For the large source, which is approximately 4 by 6 ft, 256 parabolic reflectors are grouped with individually adjustable lamps at their focal points. These reflectors are hexagon shaped for maximum density packaging. In front of the lamps and reflectors, there is a $\frac{1}{2}$-in. honeycomb 4 in. thick which is used to eliminate the stray light from the reflectors and provides a light beam collimated to approximately 4 deg of angle. The honeycomb is dipped in a nonreflective paint to minimize multiple-bounce reflections. In the center of this large source there is one vacant space. Through this area the small-angle lamp is projected. The small source is made by using a 300-w zirconium arc lamp and a projection lens 7 in. in diameter. This lens is adjusted to give collimation.

The entire sun simulation assembly is located outside the room to allow heat dispersal without affecting the thermal equilibrium of the room. Nonetheless, radiant heat from the large sun simulation causes thermal gradient effects on the vehicle simulator. Therefore, the large sun is used only for initial sun acquisition—when fine force balance of the vehicle simulator is not required.

The electrical power to the large sun is distributed to the individual lamps by using series-parallel wiring. Sixteen lamps are run in parallel, and sixteen of these parallel groups are then wired in series. This arrangement maintains the high voltage across the entire assembly and keeps the voltage across the individual lamps constant. The lamps are powered by rectified three-phase A-C, and under normal operating conditions they draw 87 amp at 112 VDC. A three-phase Variac transformer is used to control the voltage to a high-power rectifier stack.

The star simulation uses a reflecting telescope 6 in. in diameter with the light source located at the focal point of the mirror. This places the star at infinity for collimation of the light. A difficulty with this type of star simulation is the proper alignment of the star sensor and the simulation. The intensity of the lamp is controlled by an independent power source and is adjusted to the proper intensity to resemble the desired star magnitude.

The design of an air bearing specifically to reduce the turbine torques associated with it is not an easy problem. There are several ideas which attempt to explain the cause of these torques, but none at this time can be considered conclusive. The most successful method of attaining low-torque operation is to obtain a ball and cup which have a close-tolerance match and to operate them at a pressure as low as possible.

The bearings most successfully used for Boeing simulators make use of an air-bearing cup which is a multiple-orifice design with 33 metering orifices placed in two concentric circles. Each orifice is a ruby watch-jewel or platinum orifice with about a 0.14-mm hole. A cross section of the entire assembly is shown in Figure 1.

The systems are a fail-safe design in that the ball is protected should the air pressure fail. The application of flotation air creates a lifting pressure below the moving cup and between the cup and the ball. When there is sufficient pressure below the cup to support the load, it lifts the ball away from the rest cushion. Orifice sizing and the proper cup lifting area cause the ball to float when lifted from the cushion. When the air pressure is reduced, the cup retracts, setting the ball on the cushion. In this way, there is never any contact between the ball and cup. The rest cushions are made of nylon.

The bellows in the center of each assembly (except on S^3) forms an air-actuated brake. The brake is controlled by an air solenoid and provides a small amount of braking effort about the two horizontal axes to facilitate balancing of the platform.

An air-bearing platform is largely limited in capabilities by the surrounding environment. Seismic shock, air currents and temperature gradients all combine to degrade the performance of an otherwise good facility. To obviate some of these problems, Boeing has mounted the simulators on a 90,000-lb seismic slab which rests on seven Barry Controls Co. air bags. These reduce the natural frequency to about 1.5 Hz with a damping ratio of 0.5. Amplitude of motion is less than 100 μ in. reduced from the 300-μ in. background. Enclosing the facility is a double-walled room which has forced cooling air circulating between the metal inner walls and the insulated outer walls, under the slab and over the ceiling. Excess heat from the equipment and solar source is rapidly dissipated through the metal inner walls, maintaining the temperature in the room constant and within 1° F between any two points in the room. High-wattage solar sources are positioned outside the room with windows between. A new version of this facility is presently under construction at the Kent Space Center. This new facility will allow setup and operation of two small simulators simultaneously. Modifications are being made in the facility to improve its usefulness based upon the experience using the existing facility. The new facility is expected to be operational in June 1967.

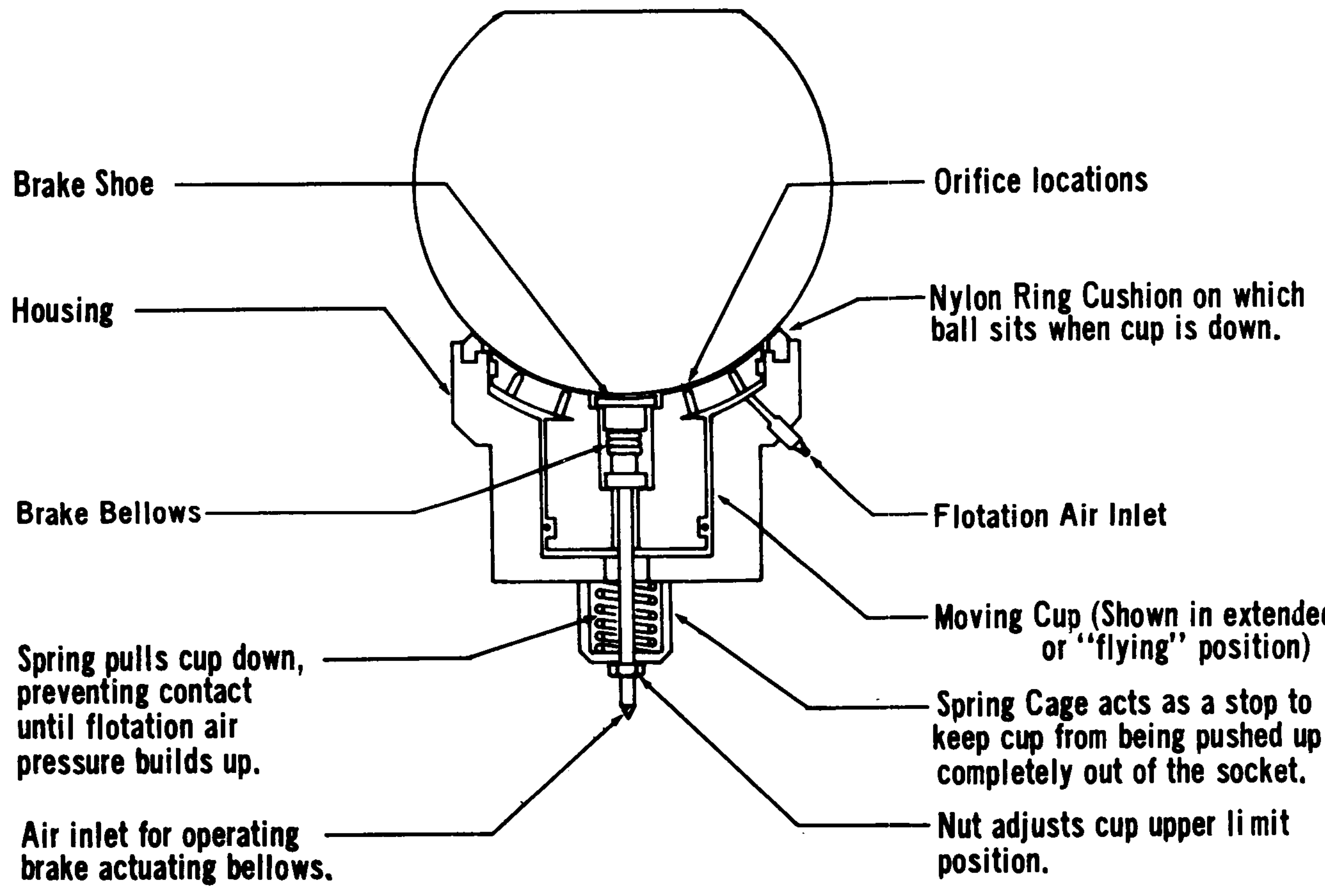

FIGURE 1. BOEING AIR-BEARING MECHANISM

The SACS Platform is a frustrum of a cone enclosed by a right circular cylinder with cutouts for equipment mounting, 80 in. in diameter and 30 in. high, trussed with triangular webs at eight points to provide a very stiff platform capable of holding a large amount of equipment with minimum deflection during maneuvers.

The S^3 Platform Simulator is structured as a box 18 in. high and 24 in. square, surrounding the air-bearing ball and 12 of the 24 batteries used, resulting in a low moment of inertia platform of almost sperical character. Provision is made on the flats of the box for mounting in pairs, four 6-ft monocoque arms which alter the configuration from a sphere to a pencil to a disc, depending on whether one or two pairs of arms are used. Spin-up capability is provided by a Varidrive unit belt coupled to a bearing assembly which supports the air bearing cup.

The High Accuracy Platform was conceived as a low moment of inertia system. This simulator consists of a box 40 in. square and 26 in. high, compartmented for storage bottles, batteries and control equipment. A three-axis CMG system has been tested on this platform demonstrating three-axis control accuracies of beter than ±0.1 arc-sec.

B. Operation

The simulator must have battery power on board to run all electrical systems for an 8-hr period. The electrical system must be capable of providing any required voltage in a regulated manner to allow operation of the several different electronic packages.

The electrical power for the simulator is provided by rechargeable nickel-cadmium batteries. The batteries are purchased as individual cells with a nominal voltage of 1.25V and a capacity of 5 amp-hr. The cells are packaged by Boeing in containers holding twelve cells in series, providing 15V, with a center-tap at 7.5V. The cells are potted in RTV Silastic, and the weights of all assemblies maintained uniform by controlling the amount of Silastic used.

The batteries for a simulator are wired to a master panel on the simulator platform which gives access to all the terminals. This panel is used to make load connections and to disconnect the batteries from the loads and place them in a series arrangement for recharging. Individual regulators have been designed to give all voltages required.

There must be a storage capability for the torquing propellant sufficient for a normal 8-hr operating day. The balance shift within the storage system as a function of propellant discharge must be minimized. The propellant system must be clean and must not introduce contamination into the thrusters and cause them to malfunction.

Hard wires to the platform cannot be used. There must be sufficient telemetry between the ground station and the platform to allow continuous monitoring of the operation of the simulator. There must be a command capability which will allow the completion of a wide variety of operational sequences with a minimum of change in the onboard electrical hook-up.

The Burner II Platform is an actual vehicle with some modifications. The solid motor case was removed to make room for the air bearing, and a mass equal to that removed was replaced.

The Docking Simulator Platform is a cockpit mounted on an air bearing, has 3 deg of attitude freedom, is dynamic and displays and uses an onboard attitude (air jet) control system.

The nitrogen that is supplied to the platform is filtered to 1-μ abs. On the platform there is another 1-μ-abs. filter ahead of the regulators. The plumbing has all been cleaned and assembled in the Boeing clean-room to a level compatible with the 25-μ-abs. level required by the thrusters. Positive pressure is maintained at all times in the gas system to prevent ingesting of particles into the gas system through the thrusters.

C. Capability

The test results indicate that the attitude control system performance can be accurately predicted if the proper care is taken in the use of the simulator. Three-axis limit-cycle rates from 2.0 to 10.0 deg per hr have been obtained on a cold gas jet attitude control system.

This simulation facility has been used for evaluation of high-pointing-accuracy systems with test results indicating that a stabilization error of less than 0.1 arc-sec is achievable with this facility; no limitation due to the facility has been identified.

The telemetry system is a standard FM-multiplexed system using the IRIC channels 5 through 13, A, C, and E. This range of sub-carrier oscillators gives the capability of measuring thruster "on" times accurate to a milli-second and has sufficient capacity to telemeter all required data. The command telemetry is accomplished by using tone-control transmitters and reed-receivers. Each transmitter has a capability of ten channels. By controlling the state of a flip-flop with each of these channels, twenty different commands can be issued to the platform. The use of diode OR-gates further expands the capability of the system if needed.

VIII. GRUMMAN AIRCRAFT ENGINEERING CORPORATION: STABILIZATION AND CONTROL SYSTEMS DYNAMIC TEST FACILITY*[16]

A. Design

The Orbiting Astronomical Observatory (OAO) air-bearing table is cruciform in planform and is broken down into eight vertical equipment bays, each pair of which uses a single vertical bulkhead to mount equipment as it will be mounted in the spacecraft. The table measures 109 in. across the arms and 80 in. in height; it has a swing radius of 72 in. and is built of aluminum. The air-bearing table, with the subsystems installed, is ballasted to duplicate the actual moments of inertia of the spacecraft to within 5 percent. Total weight of the table with the OAO performance model stabilization and control systems on board, is 5400 lb. The facility, however, is capable of supporting tables with weights up to 20,000 lb.

The facility consists of an air-bearing table which contains the spacecraft subsystems to be tested; collimators for stellar simulation; Helmholtz coils to simulate the earth's magnetic field at orbital altitudes; and an air-bearing torquer to simulate solar pressure, gravity drag and other disturbance torques in space. All this equipment is installed in a 22-ft spherical vacuum chamber mounted on a seismic foundation. An externally mounted solar simulator is used to simulate the sun.

To minimize the effects of ground noise disturbances to the systems being tested, a seismic foundation is used for the vacuum chamber and its equipment. It is a hexagon in planform, measuring 20 ft across the flats. The foundation weights 215,000 lb and is mounted on twelve springs which give the system a vertical natural frequency of 1.4 cps and a horizontal natural frequency of 0.7 cps. The seismic foundation and the vacuum pumps for the chamber are installed in a pit 10.5 ft deep, 45 ft long and 22 ft wide, covered with suitable deck plating at grade.

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*Bethpage, Long Island, New York, Spacecraft Attitude Control Laboratory.

The facility occupies 1980 ft^2 of floor space; temperature is maintained at 75° ± 1° F with a relative humidity of less than 50 percent. It is located adjacent to the clean-room in Plant 5, Bethpage, and serves as anteroom for equipment access to that facility. In order to prevent distortion of the magnetic field within the facility, all materials used have low permeability characteristics or none at all.

The 22-ft spherical vacuum chamber can be evacuated to a pressure of 750 μ—0.75 mm Hg, the equivalent of about 250,000 ft of altitude. The vacuum chamber is made of aluminum with a nonreflective epoxy black finish on its inner surface. It has a skewed primary closure which allows full access for installation of large pieces of equipment or assemblies. After all large pieces have been installed and the primary closure has been sealed, access may be had via a personnel access door large enough to allow movement of subsystem components or support equipment in and out for individual checks. Two 12-in. solar simulator ports are provided in the upper hemisphere of the chamber to permit mounting the solar simulator at different angles (vertically and 15 deg from vertical). Two viewing ports, located at eye level, provide for visual observation of the specimen during tests.

Two separate pumping systems are provided; one scavenges the air being supplied to the air bearing, and the other maintains the vacuum established in the chamber. The air-bearing scavenging system can maintain 7.5 mm Hg in the air-bearing plenum with a standard air flow of 30 cfm to the air bearing. The vacuum chamber pumping system can maintain 0.75 mm Hg in the 5600-ft^3 chamber with a through-put 3.5 cfm of standard air which comes in as leakage from the air bearing and directly from the gas jets of the stabilization and control system under tests. Each of the two pumping systems is mounted on its own seismic foundation, which has a vertical natural frequency of 2 cps to reduce transmission of pumping vibrations into the ground. Each system connects to the chamber through an equalized neoprene sleeve isolation joint which attenuates over 80 percent of the pumping vibrations.

The air bearing is used to provide a nearly frictionless support for the air-bearing table used to house the stabilization and control system under test, thus duplicating, as nearly as possible, the freedom of motion of a spacecraft in space. The air bearing has a 22-in. diameter and is made of nonmagnetic stainless steel. The bearing has a sphericity of less than 200 millionths of an in. and has better than a 4-rms finish.

The socket and pedestal which support the air bearing are designed to allow the air-bearing table to rotate freely about the vertical axis, and to pitch and yaw from the horizontal ± 30 deg. In addition, a plenum chamber is incorporated from which the air supplied to the air bearing is scavenged so as to minimize disturbance to the simulator table caused by air flow past the bearing. Scavenging this air at the bearing also makes possible maintenance of the operational altitude in the chamber with a minimum of pumping. The socket is fabricated of stainless steel and has an epoxy resin liner cast to match the air bearing.

The pedestal is a pipe 10 in. in diameter supporting the air-bearing socket. It is equipped with a caging mechanism to support the table when air is not being supplied to the air bearing. Four hydraulic cylinders with a 22-in. stroke raise or lower the support ring as required. In the raised position, the air-bearing table is raised at least 1/16 in. from its floating position; in the lowered position, clearance is provided for movement of the table.

B. Operation

A semi-automatic balancing device to drive the mass center to the center of pressure of the air bearing is installed on the OAO table. It uses two 0.25-g accelerometers as position indicators, one on the pitch axis and one on the yaw axis; their signal output is connected to a servo-drive system which actuates fine balance weights. A null signal indicates that the table is balanced across both the pitch and yaw axes; the remaining pendulosity is then determined and reduced by adjusting (by remote control) a vertical balance weight.

The OAO air-bearing table also is equipped with a mass shift compensator which is driven "open loop" to maintain the mass balance of the system during pitch and yaw motions. The system employs servo-driven weight which receives its signal from an electrolytic potentiometer which is driven to null via a cam (one on each axis) connected to the weight. The cam is designed to offset the previously determined mass shift.

To actuate these systems, to monitor the table's thermal characteristics and pitch and yaw positions, and to provide simulation of the spacecraft's separation signal, the table has its own communication system which consists of an 11-channel, 27-Mc audio modulation command receiver and a 12-channel FM-FM 217.625-Mc transmitter.

Separate control consoles are provided for operating the vacuum chamber and the facility support equipment. The vacuum chamber console presents the operational flow diagrams and is equipped with all necessary gages, meters, position indicators, recorders, switches and valve controls. The facility support equipment console is sectionalized by grouping the controls for each specific piece of support equipment; it controls the air-bearing assembly, air-bearing torquer, position readout system, Helmholtz coils, stellar simulators, seismic response, solar simulator and laboratory environmental conditions.

The facility is provided with a means of determining the fine and coarse positions of the air-bearing table during tests. This is done by mounting the spacecraft television camera on the pitch axis of the table and using it for coarse readout of the roll, pitch and yaw positions of the table. As a backup on the pitch and yaw readings, the 0.25-g accelerometers used in the semi-automatic table balancing system are also monitored. To monitor the table's motion during fine holding of the stabilization and control system, the facility uses two auto-collimators, one single-axis for roll motion and one two-axis for pitch and yaw motions. These are accurate to within 0.1 arc-sec.

Located nearby is an air-filtered and temperature-controlled room with 900 ft^2 of floor space equipped with an optical alignment fixture which is used to align optically the solar sensors, star trackers, subsystems and some of the various other components which are mounted to the air-bearing table.

Operational support equipment, including telemetry, data handling computer and recording equipment, are located adjacent to the facility in the Spacecraft Ground Control Station. The station transmits and receives data to and from the air-bearing table.

C. Capability

This facility is designed to provide a simulated environment for space conditions critical to the performance capabilities of stabilization and control systems. It is used for determining the dynamic performance characteristics of spacecraft stabilization and control subsystems with complete electronic support equipment.

The solar simulator is mounted on a movable carriage which travels on tracks on the upper part of the chamber. Its light is directed down into the chamber through either of the two ports in the upper hemisphere. It consists of eighteen water-cooled Xenon 6-kw arc lamps, mounted peripherally in a water-cooled spherical housing internally coated with magnesium oxide to reflect the generated light through an opening 7 in. in diameter at the bottom. The generated light simulates the full value of the sun in space in the 0.6- to 1.2-μ waveband at the solar sensors mounted on the air-bearing table.

Five collimators, 15 in. in diameter, located within the vacuum chamber, provide stellar simulation. Each provides a star whose angular subtense is less than 8 arc-sec with a parallax error of less than 5 arc-sec. The output of each unit may be varied to represent stars from -1.0 to +6.0 magnitude.

Three sets of Helmholtz coils are provided to simulate the earth's magnetic field at orbital altitudes. Each coil has two field windings, one fixed and one variable. The fixed field windings are used to null out the earth's field in the facility; the inputs to the variable field windings are controlled by functions generators to simulate not only the field strength at orbital altitudes, but also the changing orientation of the field as the spacecraft orbits the earth. The local geomagnetic field which is cancelled by the Helmholtz coils has a value of about 0.6 gauss at a dip angle of 7.2 deg; the residual earth's field will be no greater than 0.003 gauss. The variable magnetic field generated by the Helmholtz coils may be programed up to 0.3 gauss within an accuracy of 3 percent. The coils average 14.5 ft in diameter and are wound on self-supporting aluminum structures mounted in the chamber.

Three sets of induction torquers have been aligned orthogonally on the air bearing socket to simulate external disturbance torques, solar pressure, gravity effects, aerodynamic effects, etc., to the system under test. The torquers can provide disturbance torques of from 0 to 100,000 dynes per cm to within 5 percent accuracy. The torque is programed by means of function generators to simulate the variable resultant torque vector which acts on the spacecraft as it orbits the earth.

IX. GRUMMAN AIRCRAFT ENGINEERING CORPORATION: SPACECRAFT ATTITUDE CONTROL LABORATORY*[16]

A. Design

The air-bearing table (Figures 2 and 3) is approximately 6 ft in diameter, weighs 250 lb and can support a 750-lb test load. A threaded shaft connecting table and bearing allows the table to be shifted vertically with respect to the ball for balancing. Fine balancing of the table may be achieved by remote control. For manual balancing, fine and coarse weights are provided on the table. A Branco 10-channel radio control transmitter is used to position motor-driven weights located on each axis, and changes of 2000 dynes per cm in table balance can be commanded. Angular motion of the table during tests is measured by auto-collimators to an accuracy of 0.1 arc-sec. The angular range of motion of the table is pitch ± 45 deg, yaw ± 45 deg, and roll 360 deg. Moments of inertia for pitch and yaw are 8 and 12.5 slug/ft^2 for roll.

*Bethpage, Long Island, New York.

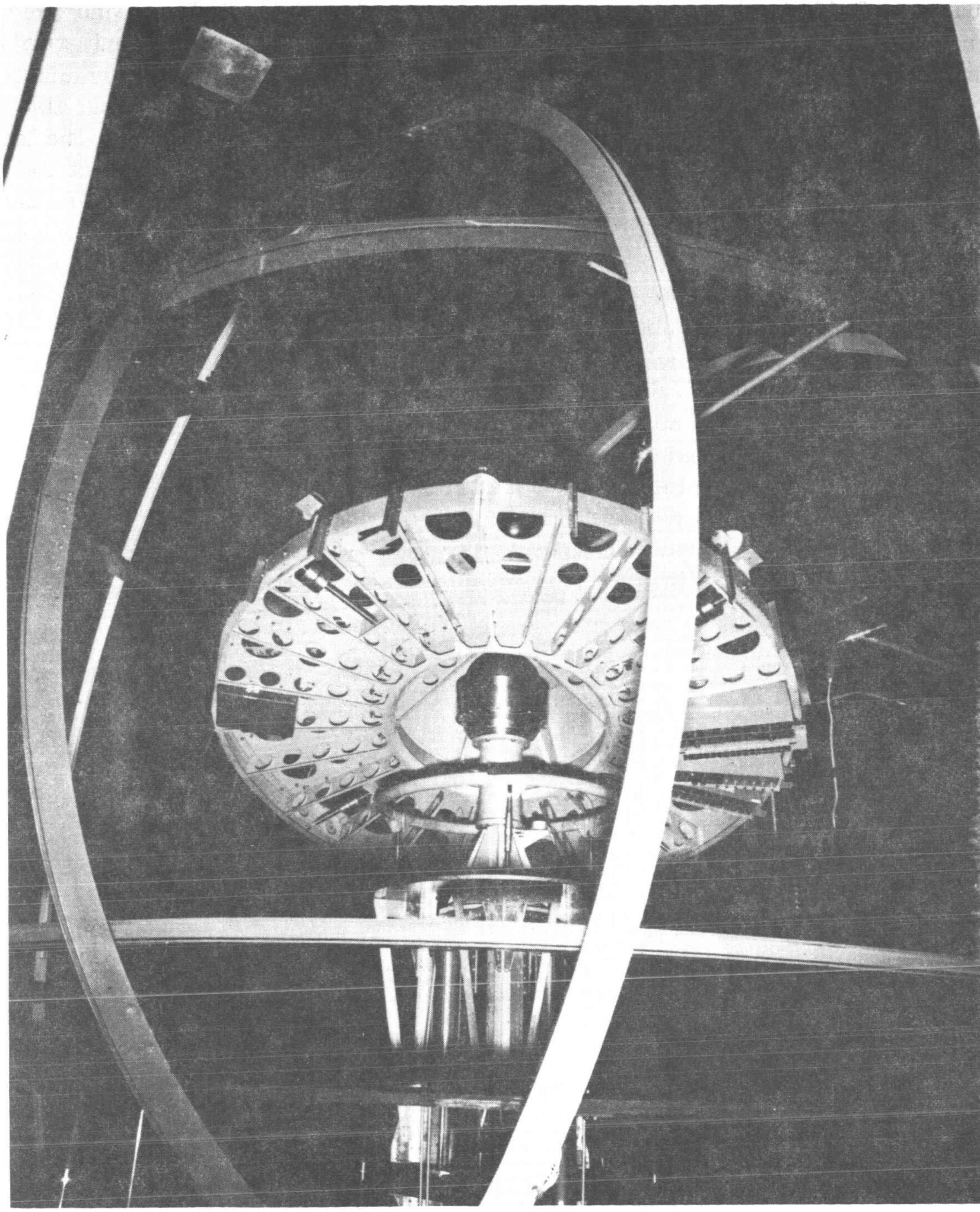

FIGURE 2. AIR-BEARING FACILITY

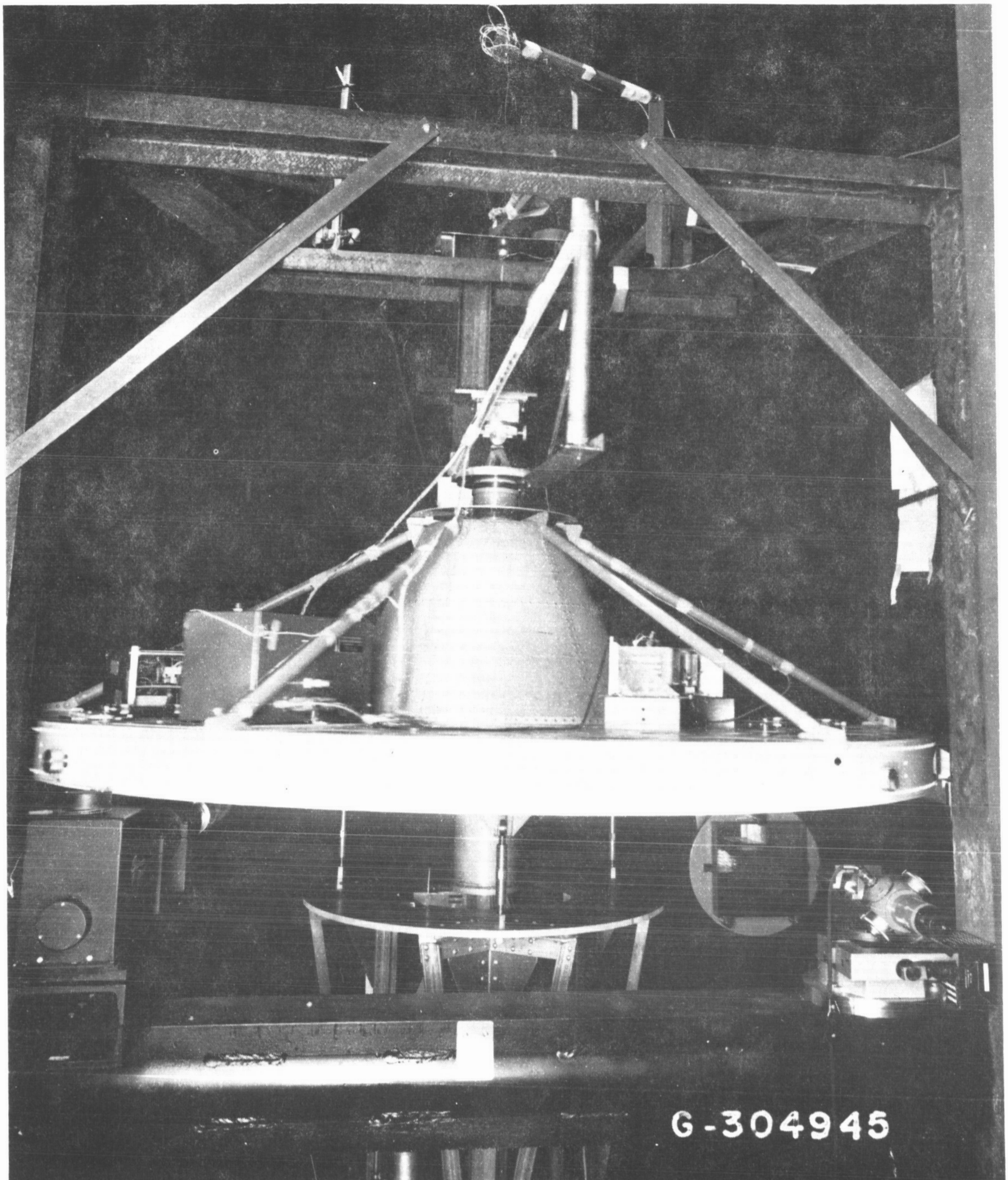

FIGURE 3. SPACECRAFT SUN SENSOR TEST SET-UP: AIR BEARING 10 INCHES IN DIAMETER

The laboratory is located in Plant 14, Electronic Systems Center, and occupies 955 ft^2 of floor space. Two adjacent rooms, each housing a Grumman-built air-bearing simulator, contain the facility.

The rooms provide a semi-clean area and are enclosed so that convection currents are kept to a minimum. The walls and ceilings of the room are painted a nonreflective black to minimize light reflection. Each air-bearing simulator is mounted on its own concrete seismic foundation to minimize ground noise effects. Observation windows are provided in each room for viewing tests. An access door in the ceiling of each room is provided for installation of a solar simulator.

The air bearing is used to provide 3 deg of freedom and frictionless support for the air-bearing table upon which the control system components under test are mounted. The nonmagnetic stainless steel air bearing, Figure 2, is 10 in. in diameter, has a sphericity of 50 millionths of an in. with better than a 5-rms surface finish. Its socket, also nonmagnetic stainless steel, is lined with an epoxy resin liner cast to match the contour of the air bearing. The socket contains a plenum chamber from which the air supplied to the bearing is scavenged to minimize disturbance to the table caused by air flow past the bearing. The load-carrying capacity of the air bearing is 1000 lb. The bearing lift-off pressure is 4 psig for a 250-lb load. With a 250-lb load and 10-psig supply pressure the vertical displacement of bearing is 0.003 in., air consumption is 0.6 scfm, and air bearing friction is 100 dynes per cm. Air is supplied to the bearing through a single 0.046-in. orifice at the bottom of the socket.

The pedestal supporting the air-bearing socket is fabricated of aluminum, and is equipped with a caging mechanism to support the table when air is not being supplied to the bearing. Three hydraulic cylinders raise or lower the support ring as required. In the raised position, the air-bearing table is raised at least 0.0625 in. from its floating position; in the lowered position, the support ring provides the limit stops for pitch and yaw.

B. Operation

To determine the position of the table during tests, a polaroid sensor is utilized for each axis. A light source mounted on the air-bearing pedestal shines through a sheet of polaroid mounted on the table axis, and then upon a polaroid sensor head. As the table rotates, the intensity of light reaching the sensor changes is proportional to the table attitude.

To command inputs to the table and monitor performance of control system components, two telemetry systems are provided. Output data from the table are transmitted via a 12-channel FM-FM 217.625-Mc transmitter to a portable ground station. Input command signals to the table are transmitted via a 10-channel audio system. The control console operates the disturbance torquers, Helmholtz coils, FM-FM and audio telemetry system, and position readout system, as well as star and solar simulators. Recording equipment in the console records test data.

In one test, the sensitivity of the table and air bearing to thermal disturbances was checked. Thermal disturbances are simulated by lamps mounted under the table to produce thermal currents capable of inducing table motion disturbances on the order of 25,000 dynes per cm. The remote control transmitter and control unit are used to position motor-driven weights on the table to establish accurate balance and pendulosity prior to the test and to counteract thermal disturbance torques during the test.

C. Capability

One air bearing is equipped with Helmholtz coils and is utilized in the development of spacecraft stabilization and attitude control systems. Another is used to test advanced development sensors and control components for spacecraft attitude control systems.

Three sets of Helmholtz coils--each with two field windings, one fixed and one variable--are provided to simulate the earth's magnetic field at orbital altitudes. The fixed windings are used to null out the earth's field in the room. Variable field winding inputs are controlled by function generators to simulate not only the field strength at orbital altitudes but also the changing orientation of the field as the spacecraft orbits the earth. The local geomagnetic field which is cancelled has a value of 0.6 gauss at a dip angle of 7.2 deg. The residual earth field will be no greater than 0.003 gauss. The variable magnetic field generated by the Helmholtz coils may be programed up to 0.3 gauss. The coils average 11 ft in diameter and are wound on self-supporting aluminum structures.

Three sets of Induction Torquers have been aligned orthogonally on the air-bearing socket to simulate external disturbance torques. Disturbance torques from 0 to 75,000 dynes per cm can be produced by the torquers. Torque is programed by a function generator to simulate the variable resultant torque vector which acts on the earth-orbiting spacecraft.

The Solar Simulator is located directly above the access door in the ceiling of the room, and consists of four floodlights mounted in an air-cooled box.

The light is directed through a Fresnel lens down into the room. To simulate the star tracker control during tests, a simulated star tracker is mounted on the table, and a simulated star source is mounted in the room. The star tracker simulator consists of an XY20D Micro systems radiation tracking transducer. This photo-voltaic device detects the position of visible-to-near infrared radiation simultaneously in two axes. The star source consists of a Sylvania glow modulator tube R1131C.

The dynamic evaluation of a prototype spacecraft sun sensor and associated control system, Figure 3, was performed on the 10-in. air-bearing simulator. The air-bearing simulator was restrained to operate about the vertical axis only because the sensor tested was a single-axis device. A rigid structural A-frame was built around the simulator, and served to support the instrument-bearing block which is used to restrict the air-bearing table motion to a single degree of freedom. This axis was aligned to within 1 arc-min of the local vertical. Electrical connection to the table was accomplished by an overhead flexible wire configuration. Since table deflections during this test were limited to ±5 deg, the measured disturbance torque of ±1200 dynes per cm due to flexible wire bundle was within limits specified for proper control system operation.

During this test, sun sensor, twin gyro torquer and associated electronic equipment were mounted on the table. A Grumman-designed collimated light source was used as the solar simulator. Static calibration of the control system was achieved using an auto-collimator mounted on a Gurley Unisec assembly. An optically flat mirror mounted on table served as a readout reference. The basic accuracy of this measurement system was ± arc-sec. Electronic measurement and control equipment were housed in a control console adjacent to the simulator. Sensor accuracy during the dynamic test was evaluated to better than ±1 arc-sec.

This simulator was utilized in the development of the OAO spacecraft stabilization and control system and may also be utilized in the development testing of similar types of spacecraft attitude control systems.

For the OAO Stabilization and Control System Test, the facility consists of a development model of the control system mounted on an air-bearing table, Helmholtz coils to simulate the earth's magnetic field at orbital altitudes, air-bearing torquers to simulate spacecraft disturbance torques, solar simulator, star tracker, and table attitude and rate readout system.

X. GRUMMAN AIRCRAFT ENGINEERING CORPORATION: ROTATING INERTIAL SIMULATOR* [16]

A. Design

The 6 in. platform in Figure 4 is fabricated of aluminum structural shapes, is 4 ft in diameter, weighs 50 lb and can support a 300-lb test load. All equipment and power supplies are fastened on the platform with bolts and are easily adjusted or removed. A threaded shaft connecting platform and bearing allows the platform to be shifted vertically with respect to the bearing for balancing. A set of movable weights is located on the two major horizontal axes beneath the platform for horizontal balance. For adjustment of the inertia ratio between the major horizontal and vertical axes, provision is made on top and bottom of the platform for the addition of ring weights. The inertia ratio is adjustable from 0.7 to 1.5 in 22 incremental steps. Inertia about the vertical axis is 15 and 10 slug/ft^2 about the two major horizontal axes. Platform motion about the horizontal axes is restricted to ± 20 deg.

The 6-in. air bearing is made of nonmagnetic stainless steel, has a sphericity of better than 50 millionths of an in., with less than a 5-rms surface finish. The air bearing socket, also made of nonmagnetic stainless steel, is lined with an epoxy resin liner cast to match the contour of the air bearing. The load-carrying capacity of the air bearing is 350 lb. To support this load an air supply pressure of 16 psig is required. Air is supplied to the bearing through a single 0.062-in. diameter orifice at the bottom of the socket.

B. Operation

The platform spin mechanism consists of a motor tachometer drive assembly located in a movable arm above the platform. Platform speed is selected at the console and can be varied from 0 to 30 rpm. Adjustable spin and disturbance jets are mounted on the simulator to maintain spin speed and to provide a disturbance torque pulse to the platform on command from the programer. The nitrogen gas for the jets, 240 in.^{3}, is stored in gas bottles at 3000 psi.

A 4-channel pen motor recorder is mounted on the platform. Two channels are connected through recorder amplifiers to the sun sensor under all tests. The two remaining channels can be connected through recording amplifiers

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* Bethpage, Long Island, New York.

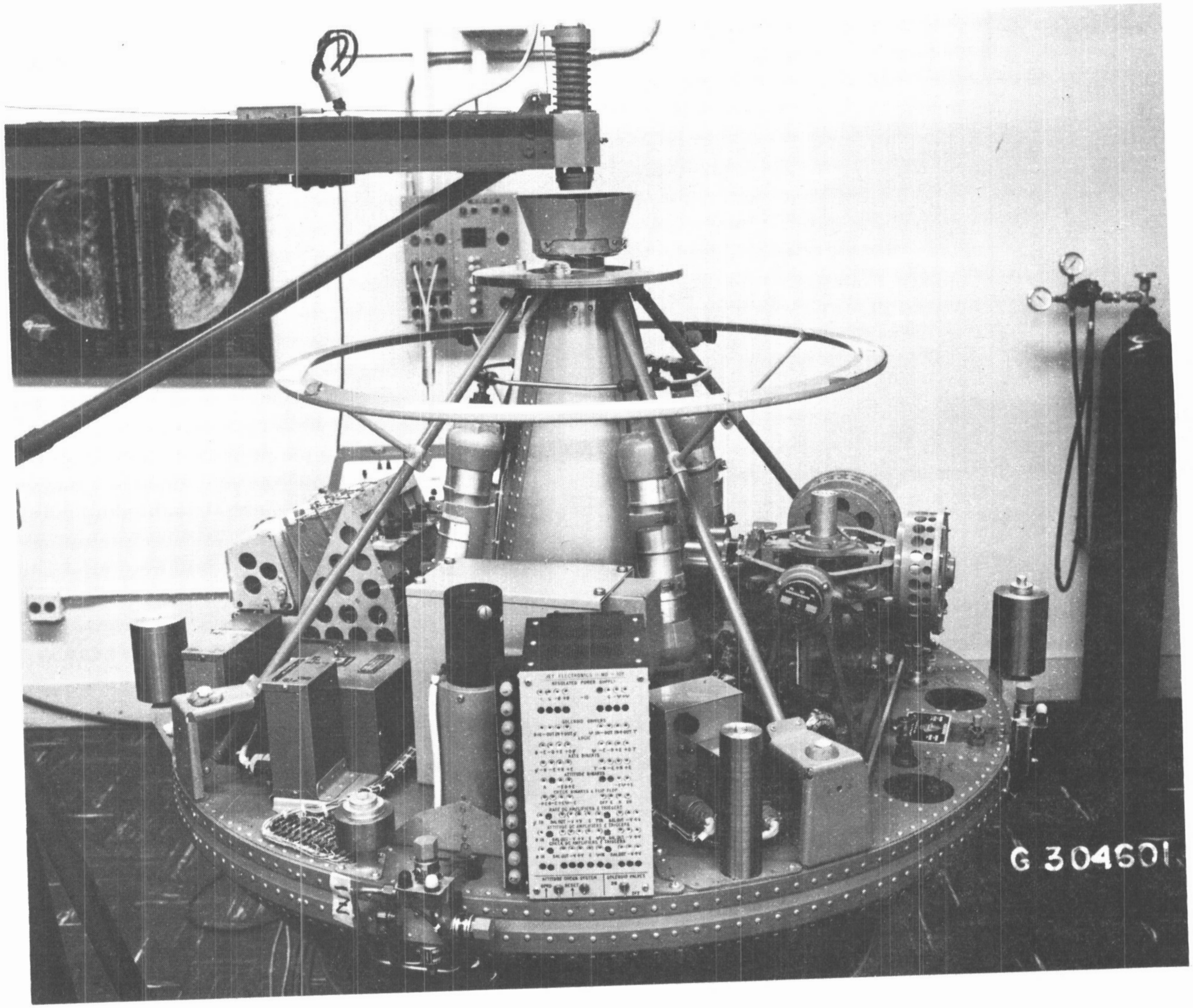

FIGURE 4. JET DAMPER CONTROL SYSTEM SET-UP: AIR BEARING 6 INCHES IN DIAMETER

either to the rate gyros or for recording any other signals from equipment under test. Chart paper is looped to prevent mass shift during recording. Available chart speeds are 1 and 2.5 mm per sec.

The programer on the platform consists of a 400-cps motor driving cam-operated switches. These switches control the sequence of events on the platform, and shut off the programer motor at the end of each cycle. The programer cycle is approximately $4\frac{1}{2}$ min long.

Solar simulation is provided by a 500-w lamp mounted on the ceiling directly above the rotating inertial simulator.

C. Capability

The Wobble Damper Control System, the Jet Damping and Orientation Control System and the Passive Fluid Ring Damper System were built and evaluated on the rotating inertial simulator. The Wobble Damper Control System, developed to stabilize the simulated rotating space station, derives control torques from the precession torques generated by a spinning wheel mounted in servoed gimbals. The spin axis of the control wheel is aligned with the spin axis of the platform. The rate gyros and sun sensor supply rate and attiude error signals respectively to the two gimbals which carry the spinning wheel. The momentum of the control wheel and gain of the gimbal servo system can be varied over wide ranges. The spin wheel inertia is 1×10^{-3} slug/ft^2 and its speed can be varied from 0 to 5000 rpm.

The Jet Damping and Orientation Control System, shown in Figure 4, developed to stabilize the simulated rotating space station, derives control torques from the thrust generated by four pneumatic pulse jets located at each end of the two major horizontal axes. The simulated rotating space station is initially rate stabilized, but its spin axis may gradually depart from the sun line because of disturbance torques. If the attitude error exceeds the check limits, attitude control is turned on to realign the station spin axis with the sun line. When attitude error falls below the attitude limit, attitude control is turned off. Means are provided for demonstrating the effectiveness of the control system by adjusting the deadband controls and by turning off sections of the control system.

The jet control system electronics consists of an attitude control section, rate control section, check control and a logic section. These sections consist of D-C wipeout circuits, deadband limits control, D-C amplifiers, voltage sensing trigger circuits, logic circuits, and solenoid drive amplifiers.

The Passive Fluid Ring Damper System consists of a tubular ring filled with fluid and is mounted in a plane parallel to the simulator's axis of symmetry. The simulator platform is spun up to the desired speed and then disturbed by means of jet pulsing. A motor-driven valve, controlled on command from the programer, opens and allows the fluid to flow within the tubular ring, thereby damping the platform wobble motion. Viscosity of the fluid was varied during tests by the use of different mixtures of water and glycerol.

XI. THE BENDIX CORPORATION, NAVIGATION AND CONTROL DIVISION: SATELLITE ATTITUDE MOTION SIMULATOR*[20]

A. Design

The total platform and stabilization system weight is 460 lb. The platform has been suspended using 0.87 ft^3/min air flow at the positive lift-off pressure of 6 psig. The platform motion is limited to 360 deg in roll axis, and ±45 deg in yaw axis. An alternated method provides all the equipment described plus an equipment platform with the general shape of a frustrum of a cone and is constructed of aluminum and magnesium which attaches to the ball and cap assembly.

An adjustable platform support is provided to limit angular motion of the ball and platform assembly during installation of equipment and subsequent balancing operations. This support may also be adjusted to remove the load from the air bearing during stand shut-down. A vertical weight adjustment is provided for the purpose of raising or lowering the center of mass of the "free" platform to its optimum coincidence with the center of rotation.

The bearing is a 16-in. hollow aluminum ball lap-fitted to a socket in the supporting pedestal. The ultimate load carrying capacity of the bearing is approximately 3000 lb using low pressure air (60 psig max).

The attachment design of the ball and cap assembly permits the addition of a knife-edge support assembly for single-axis simulation. This knife edge assembly has been designed as a completely bolted-on structure for easy installation and removal.

The ball socket is provided with a scavenging device consisting of an annular leakage collection groove and four equally spaced air exit passages. The tubing leading from these passages is routed inside the pedestal column with the external air bearing supply line and exits through the base for convenient

* Teterboro, New Jersey.

connection to an external pump. This scavenging of air will permit better utilization inside a vacuum environmental chamber.

B. Operation

A typical control system test consisted of a Bendix Sun Sensor as a reference source, a Bendix Reaction Wheel as a control actuator, and a pair of cold gas jets to unload the wheel when it becomes saturated.

The sun sensor and an all-gas control system function for initial acquisition of references from the "tumbling" platform, whereupon the three-axis reaction wheel system will control the reference information supplied by the star tracker assemblies.

The sun sensor consists of a shadow cast aperture which changes the area of sunlight that falls on an array of photo-voltaic silicon solar cells, as a function of the angle to the sun line. The output of the sensor is linearly proportional with angular displacement to within 1 percent for angles up to ±10 deg from the bore sight axis of the sensor. For angles from 10 to 90 deg from the axis, the output continues to increase with angle.

Platform operating power is supplied by a battery and an A-C static converter.

C. Capability

This control system makes use of such items as the inertia wheel and sun sensor which were developed by Eclipse-Pioneer and thrust controllers which were developed by Bendix Research Division.

The simulator may be used to evaluate control systems, adaptive to current satellites and to those planned for the near future, and to the control system mechanizations planned for use over the next two or three years.

XII. ATLANTIC RESEARCH CORPORATION, MISSILE SYSTEMS DIVISION: GAS-BEARING DYNAMIC SIMULATOR*[27]

A. Design

The principal element of the simulator is a 16-ft beam supported by a 10-in. sphere at the boom's center of gravity, shown in Figure 5. The weight concentrated at this position is approximately 1600 lb including detachable weights. These weights are of such a magnitude and are so positioned as to balance the boom about the supporting bearing while duplicating the polar and transverse moments of inertia of the system being tested. The boom is supported by the gas-bearing seat mounted at the top of a 4-ft pedestal.

The bearing seat is connected to a remote source of nitrogen capable of supplying the bearing with gaseous nitrogen at pressures up to 150 psig. At this operating pressure the bearing will support over a ton. The bearing and boom assemblies are protected against shock and other mishaps occasioned by overtravel of the angular bearing limits during simulator motion in the limited axis of freedom. This protection is afforded by a rubber-cushioned snubber ring mounted to the pedestal base. This ring is capable of being raised and lowered to either of two operating levels. In the upper position the snubber ring is brought up against both arms of the boom, causing the boom assembly to be caged in horizontal position during periods of inactivity. In the lower position, the snubber ring functions as a motion limiter in the manner previously described.

The boom contains features incorporated to facilitate adjustments and measurement of the device's polar and transverse inertias. Balance adjustments about all three axes, as well as the aforesaid inertial moment variability, are provided for by the positioning of taped and threaded weights of varying masses on four radially disposed, threaded posts mounted on each of the boom arms. At two positions, equidistant from the boom support point, aluminum rings with peripheral grooves are installed. The polar moment of inertia is measured by using known weights attached to strings wound in these grooves. The transverse moment of inertia is determined by placement of a known weight at some position along the length of the boom. No specific design feature is identified with this latter measurement.

The test boom travels in the horizontal plane to allow a full 360 deg of pitch movement; 360 deg of roll also is provided. Any movement in the vertical plane represents yaw. Approximately 45 deg of movement in this direction is permitted by fixture design. On the air-bearing device itself, the polar and

*Costa Mesa, California.

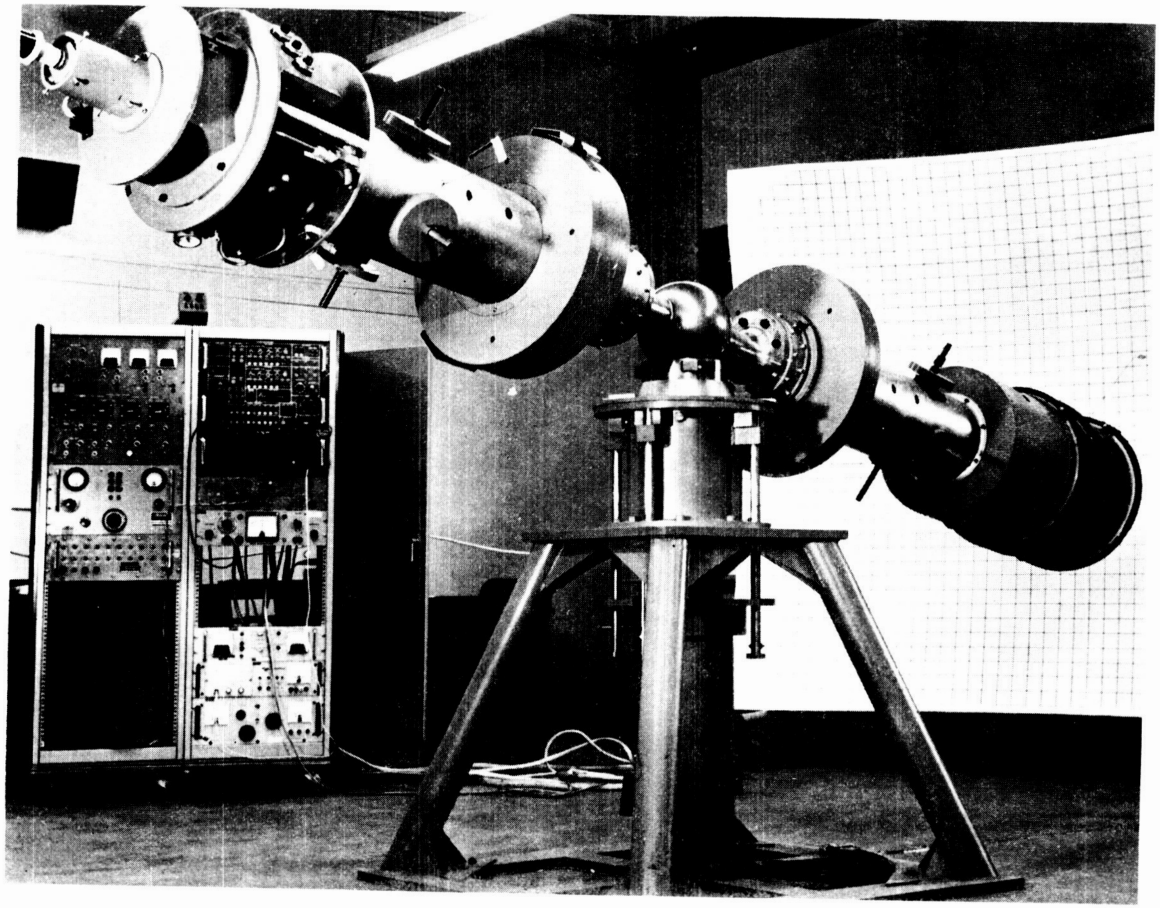

FIGURE 5. ATHENA SYSTEM SIMULATOR

transverse moments of inertia, initial yaw, pitch and roll velocities, degree of dynamic balance or imbalance, all appear capable of being varied to simulate precisely the control condition desired.

A rechargeable battery is used to supply primary power for all simulator systems. The capacity of this power source will sustain up to 6 hr of continuous test operations. The recharge cycle is 16 hr.

B. Operation

For the Athena program, the attitude controller is mounted at one end of the boom. Its control jets are about 5 ft from the boom center. Mounted with the control device is an FM-FM telemetry system for relaying certain conditioned telemetry signals from the attitude controller during flight simulations. These signals are received in a standard van-mounted telemetry ground station.

As the simulator rotates and the coning period increases, read-time telemetry monitors are observed to verify that the angular rates are within the parameters defined for the particular test sequences. Visual and / or photographic observation of the simulator motion may be made using the cross-hair projected from the simulator's longitudinal axis. When the angular rates are within limits, and the roll angle such that roll error will be 180 deg after rate arrest, the attitude controller is commanded to start by means of the command receiver loop.

A Jet Power Pack is mounted at the end of the beam opposite to the control device. The weight of this system and all ancillary equipment is such as to provide a reasonable static balance of the boom assemblies under operating conditions. The Jet Power Pack contains spherical reservoirs for the storage of nitrogen at 5000 psig. This gas supply is plumbed in parallel with the attitude controller supply to provide the extra gas required by the controller while operating in the atmosphere and to maintain boom balance as the nitrogen supplies are depleted. The Jet Pack nitrogen is also used to provide triaxial reaction impulse to the boom through six electrically controlled nozzles. The "on" time of these nozzles is controlled by adjustable timers started by radio link; the timers and nozzles are utilized to provide desired initial roll and coning rates for the control system experiment being conducted. The Jet Power Pack also contains a command-receiver/decoder unit to provide the start signal for the nozzle timers and the additional control pulses necessary to acquire the desired initial conditions. The command receiver also provides necessary control functions for the attitude controller.

Mounted on the longitudinal axis of the simulator, at the Jet Power Pack end of the boom is a set of projection optics arranged to project a cross-hair reticle outwards onto target screens. Grid lines on the target screens enable the simulator's movements to be observed and recorded photographically. The initial conditions for a test run are established by manually positioning the boom and applying, through the Jet Power Pack reaction jets, two programed impulses, one about the roll axis and the other about the transverse axes for yaw and pitch error. Programing of the reaction jets in the proper sequence-time relationship introduces simulator roll and coning rates approximating those anticipated in flight.

A power pack using reaction jets identical to those on the attitude controller located at the opposite end of the boom imparts the desired test conditions to the simulator. As the simulator rotates, real-time telemetry monitors are observed to verify that the angular rates are within the parameters defined for the particular test sequence. Visual and/or photographic observation is made on the initial condition screen by the cross-hair projected from the simulator's longitudinal axis. When all conditions are go, the controller aligns the yaw axis while performing the pitch-over maneuver.

C. Capability

The simulator was designed and developed to simulate the dynamic characteristics of the reentry velocity package of the Athena system, attitude controller and the third stage telemetry system. It simulates the mechanical, electrical and dynamic characteristics of a body entering the earth's atmosphere. Instrumentation can be added or deleted from the experiment as required, although a highly instrumented experiment might require an augmentation of the existing number of telemetry channels. Parameters of the reaction impulse system which appear capable of being varied without difficulty are number and physical orientation of the jet valves, jet valves impulse, control moment, simulated gas storage capability, type of impulse, i. e., discrete or proportional control, and others. There are many signal processing network parameters capable of being varied. A few of the possible uses are event timing and sequence, amplifier channel gains, system dynamic response, simulated control valve lags, pseudo-rate derivation, rate-to-attitude gain, filter time constants, system phase shifts, simulated body bending characteristics and many other uses.

XIII. LTV AEROSPACE CORPORATION, MISSILES AND SPACE DIVISION: AUTOMATIC CONTROLS EVALUATION SIMULATOR*[22]

A. Design

The Automatic Controls Evaluation Simulator (ACES) is a research tool and design aid which has a framework that reproduces the inertial characteristics of typical space vehicles.

The moment of inertia is variable upwards from a minimum of 50 slug/ft^2 in pitch and yaw, and 10 slug/ft^2 in roll. Values are dependent on equipment requirements, and maximum inertias are limited only by maximum gross weight of 1500 lb.

The rotation is limited in pitch and roll to ±35 deg before contacting energy absorbing system. Yaw angle limits are dictated by umbilical effect on the test being performed; they are unlimited without a cable.

The reaction jets, two each having 10 lb of thrust in pitch and yaw and four in roll having 2 lb of thrust per valve, have adjustable thrusts up to 15 lb by varying pressure and orifice. All valves are ON/OFF solenoid operated.

The pressure source for reaction jets consists of two 2650-in.^{3}, 3000-psi tanks available for reaction control approximately equivalent to an impulse of 2000 lb-sec.

The air bearing is a 4.5-in. diameter steel ball fixed to the simulator frame and floating on nitrogen at 125 psi.

B. Operation

The platform floats on an air bearing and may be controlled either manually by a pilot in the cockpit or operated unmanned from a remote console. The simulator frame, which is 12 ft in length, carries nitrogen tanks to supply gas to the reaction jets. An electronics package on the front of the frame contains amplifiers, demodulators, and rate and attitude gyros. With an onboard instrumentation package and auxiliary recording equipment, the following can be recorded: (1) control inputs in pitch, roll and yaw; (2) attitude and rate gyro output for each axis; and (3) reaction jet thrust and valve signal. Recording capabilities can be expanded as required. Electrical power and connections to

*Dallas, Texas.

the remote console are supplied through a flexible umbilical cable. However, if conditions dictate, the umbilical cable can be removed and a power source mounted aboard the frame.

C. Capability

Typical facility applications are component evaluation, control parameter optimization, system development and system integration. Test items may include moment producing sytems, reaction jets, reaction wheels, gyros, and reference systems, inertial and tracking.

XIV. AVCO SPACE SYSTEMS DIVISION: AIR-BEARING TABLE*[23]

A. Three-Axis Air-Bearing Table

A three-axis air-bearing table has been designed and built at Avco to provide a means of simulating vehicle dynamics for the evaluation of vehicle attitude control systems. Salient features of the table are as follows:

Gimbal Freedom

X-axis = unlimited

Y-axis = ± 35 deg

Z-axis = ±35 deg

Bearing Disturbance Torques: 7000 dynes per cm

Eccentricity of Ball: 0.0002 in.

Diameter of Ball: 10 in.

Load Capacity: 600 lb nominal

Readout: Visual - Collimated light sources mounted to table structure

*Wilmington, Massachusetts.

B. Three-Axis Miniature Air-Bearing Table

A three-axis air-bearing table smaller than the above table has been designed and built at Avco. The principal characteristics of the table are as follows:

Gimbal Freedom

X-axis = unlimited

Y-axis = ± 45 deg

Z-axis = ± 45 deg

Bearing Disturbance Torque: 3 dynes per cm

Eccentricity of Ball: 0.0001 in.

Diameter of Ball: 6 in.

Load Capacity: 30 lb

Readout: Visual - Collimated light source mounted to the table structure

C. Three-Axis Air-Bearing Table

An air-bearing table is being developed at Avco to provide lower uncertainty torques and more angular freedom than existing units. The table will have a specially designed outer rim plenum so that when it is connected to a vacuum pump, it can be operated in a vacuum chamber. The principal characteristics of the table being designed are as follows:

Gimbal Freedom

X-axis = unlimited

Y-axis = ± 30 deg minimum

Z-axis = unlimited

Disturbance Torques: less than 500 dynes per cm

Eccentricity of Ball: less than 10 μ in.

Diameter of Ball: 7 or 10 in. (decision not final)

XV. GENERAL ELECTRIC COMPANY: SPACECRAFT CONTROL LABORATORY*[24]

A. Design

The Avionic Controls Department (ACD) of General Electric Company has two air-bearing simulation facilities. Table II summarizes characteristics of the vehicles presently being used in conjunction with the air bearings. There has been some attempt to control the laboratory environment by enclosing the facilities with ceiling to floor drapes, closing off air conditioning ducts, and isolating various equipment such as the air compressor.

Table III summarily describes the two air bearings. In addition to those characteristics listed in the table, the bearing support in facility 1 is crooked to allow increased vehicle motion. This support is mounted on an azimuth ring which can be rotated to simulate an orbiting satellite's pitch rate. The two-bearing support of facility 2 restricts vehicle motion to 1 deg of freedom. The axis of freedom is horizontal.

B. Operation

Both facilities were designed to simulate space vehicle attitude motion and are equipped with control moment gyros, reaction control system hardware, and the necessary electronics to provide closed-loop attitude control. Accurate measurement of the control performance of such systems requires monitoring the attitude of the simulated vehicles without physically disturbing them. Thus, vehicle attitude measurements are made by means of a special auto-collimator installed in the laboratory. Commands to the vehicles are delivered via a radio link to receivers on the equipment platforms, and experimental data are transmitted from the vehicles to laboratory recording equipment by a multi-channel telemetry system.

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*Binghamton, New York.

Table II. Vehicle Characteristics

Vehicle Characteristic or System	Facility 1	Facility 2
Weight (lb)	1800	500
Inertias ($Ft-lb-sec^2$) (z-axis vertical)	I_{xx} = 30 I_{yy} = 200 I_{zz} = 200	I_{xx} = 18
Size (in.)	x - 96 y - 40 z - 31	$\left.\begin{array}{l} x - \\ y - \end{array}\right\}$ 60 (diameter) z - 18
Structure/ material	Box frame/ aluminum	Aluminum
Balancing technique	Manually adjusted weights	Manually adjusted weights
Electric power supply	Lead-acid batteries 400 & 60 cps inverters	By fine wire
Position sensors	Optical system using photo pots	Optical system using photo pots
Command/control	5-Channel radio control system (vibrating reed type)	By fine wire
TM	6-Channel FM multiplex	By fine wire
Attitude control	Control moment gyros plus cold gas reaction thrusters. GN_2 stored on board.	Control moment gyros
Auxiliary equipment on board	Transistor analog computer	———

Table III. Air-Bearing Characteristics

Vehicle Characteristics or System	Facility 1	Facility 2
Bearing size	10-In. sphere	10-In. sphere & auxiliary 2-in. sphere to eliminate 2 deg of freedom
Bearing material	Stainless steel	Stainless steel
Bearing seat material	Teflon	Teflon
Gas supply	Air from separate compressor with dust filters and moisture traps. Stainless steel distribution components.	
Supply pressure (nominal — psi)	80	40
Static friction (in-lb)	< 0.07	0.004*
Damping (in.-lb/rad/sec)	—	1.4*
Pedestal capacity (lb)	4000	10,000
Vehicle docking	Mechanical plus magnetic release	Mechanical
Mounting pad	6-In. concrete floor	6-In. concrete floor

* With 300-lb vehicle.

C. Capability

The facility permits evaluation of developmental spacecraft attitude controllers aboard simulated vehicles. The laboratory is being used to investigate various momentum-wheel controller. System tests have been primarily aimed at the unmanned satellite stabilization problem.

XVI. JET PROPULSION LABORATORY*[7]

The Jet Propulsion Laboratory platform is very stiff, consisting of heavy metal plates in a webbed construction. Deformation unbalance is below 10 g/cm. The use of stainless steel minimizes magnetic torque. The bearing support permits tipping more than 90 deg. The weight is 800 lb without equipment. Data transmission is handled by a 30-channel telemetry system (no wire attached to platform). Sealed nickel-cadmium batteries power the platform. Balancing is provided by automatic weights driven along the three-axis in response to gyro signal. The bearing is a 10-in. beryllium sphere and is spherical to $\pm$ 30 μ in. Air at 140 psi enters the cup through two concentric rings of air jets. The diameters of the rings are 1.5 in. and 3.6 in. with 10 and 23 jets, respectively. A nylon ring supports the ball when the air pressure is off. The attitude controls are gyros, sun sensors, canopus sensors and control jets.

XVII. AMES RESEARCH CENTER**[7]

The man-carrying platform at Ames Research Center weighs 1800 kg and is supported by a 24-cm ball in an epoxy resin seat by 300 psi air through a single hole in the bottom. Motor-driven weights along the three-axis balance the platform. The attitude is controlled to 5 arc-sec. Attitude sensors are star trackers with a resolution of 2 arc-sec. An example of equipment evaluated is the use of twin gyros as an attitude control torque source.

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* Los Angeles, California.

**Moffett Field, California.

XVIII. LANGLEY RESEARCH CENTER*[7]

The Langley Research Center is known to have platforms supported by a 6-in. stainless steel ball in an epoxy resin seat and a 3-in. brass ball in an aluminum seat. Air is supplied to the 6-in. bearing at 20 psi and admitted through a 0.09-in. hole in the bottom of the seat and to the 3-in. bearing at 15 psi through 12 holes around the cup. A wobble damper for spinning satellite was investigated on the larger platform and a satellite control system using inertia wheels and large bar magnet on the smaller platform. Small coiled wires were used to transmit data and power.

XIX. MARSHALL SPACE FLIGHT CENTER**[7]

The Marshall Space Flight Center is known to have an extremely rigid, symmetrical disc-shaped platform mounted on a 10-in. aluminum sphere. A manufacturing tolerance of 10 μ in. and a large moment of inertia are provided with minimum mass. Nonmagnetic materials (aluminum), treated to prevent warping, are used. Rigid attached components reduce deformation unbalance. The support permits 120-deg roll and pitch and unlimited freedom in yaw. Steel strips compensate for temperature effects; cantilever springs with weights compensate for anisoelastic torques. Propellant cavities are coincident with the center of rotation. Unbalance torques are computed from angular acceleration about each axis with platform constrained to move about one axis by use of small auxiliary spherical air bearing. Unbalance from heating is partially solved and air temperature and circulation is controlled. Anisoelasticity is solved by a cantilever spring mass compensator. Helmholtz coils neutralize the earth's magnetic field. The battery selection reduces torque due to angular position and discharge, and solid state switching reduces unbalance. Data transmission is by telemetry. There are no external connections.

XX. UNITED AIRCRAFT CORPORATION†[7]

The platform is 5 ft in diameter and weighs 8000 lb. The ball clears the seat by 0.001 with this load. It is supported by a 16-in. ball with 100-μ in.

*Langley Field, Virginia.

**Huntsville, Alabama.

†Windsor Locks, Connecticut.

sphericity and a finish to 5 μ in. Nitrogen at 250 psi, 12 cfm supports the ball. Air flow, temperature and cleanliness are closely controlled. Batteries power the platform equipment. A three-axis gimbal system utilizes an auto-collimator signal to track the platform with an accuracy of a few arc-sec.

LITERATURE CITED

1. Bachofer, B. T. and L. T. Seaman, ONE-ARC-SECOND SIMULATOR FOR ORBITING ASTRONOMICAL OBSERVATORY. Presented at American Institute of Aeronautics and Astronautics, Annual Meeting, 1st, Washington, D. C. 29 June - 2 July 1964, Paper 64-205. Also in Journal of Spacecraft and Rockets, 2, March - April 1965, pp. 260-262, A65-20969.

2. Arizona State University, Tempe, Arizona, ATTITUDE STABILITY OF A SPINNING PASSIVE ORBITING SATELLITE by Leonard Meirovitch and Frank B. Wallace, Jr., Report No. NASA CR-665. Prepared for National Aeronautics and Space Administration under Contract No. NGR-03-001-014.

3. General Electric Company, Johnson City, New York, ATTITUDE CONTROL AND STABILIZATION SYSTEM FOR AN ORBITING VEHICLE Technical Report, July 1962 - August 1964 by K. B. Haefner, May 1965, Report No. AFFDL-TR-64-165, X65-19402#, AD 468 353. Prepared for Wright-Patterson Air Force Base, Ohio, under Contract No. AF 33(657)-9180.

4. Dusterberry, J. C. and R. M. Barnett, MULTIPURPOSE RESEARCH LABORATORY FOR FLIGHT SIMULATION, ASME--Paper 63--AHGT--87 for meeting 3 - 7 March 1963.

5. Dittmar, David N., SIMULATION OF A SATELLITE MAGNETIC STABILIZATION SYSTEM IN AN AIR BEARING FACILITY, Institute of Electrical and Electronics Engineers, Annual East Coast Conference on Aerospace and Navigational Electronics, 12th, Baltimore, Maryland, 27 - 29 October 1965. Technical Papers, A66-19514.

6. Naval Air Test Center, Patuxent River, Maryland, EVALUATION OF PROJECT MERCURY SIMULATOR by R. E. Solliday, February 1961, Report No. 1, AD 471 781.

7. Smith, G. Allan, DYNAMIC SIMULATORS FOR TEST OF SPACE VEHICLE ATTITUDE CONTROL SYSTEMS, Virginia Polytechnic Institute The Role of Simulation in Space Technology, 1964, N65-33615.

8. Sandia Corporation, Albuquerque, New Mexico, GAS BEARING ATTITUDE CONTROL SIMULATOR by D. R. Schafer, April 1965, Report No. SC-TM-65-93, N66-13145#.

9. Wilcock, D. F., DESIGN AND PERFORMANCE OF GAS-PRESSURIZED, SPHERICAL, SPACE-SIMULATOR BEARINGS, American Society of Mechanical Engineers and American Society of Lubrication Engineers, International Lubrication Conference, Washington, D. C., 13 - 16 October 1964, Paper 64 - Lub-16, A65-11669.

10. Honeywell, Aeronautical Division, SPACECRAFT DYNAMICS SIMULATOR, pamphlet, no date.

11. The Boeing Company, Space Division, Seattle, Washington, THE LUNAR ORBITER ATTITUDE CONTROL SIMULATOR by Douglas C. Fosth, January 1965.

12. George C. Marshall Space Flight Center, Huntsville, Alabama, THE POSITION OF MSFC IN THE STATE-OF-THE-ART OF ATTITUDE MOTION SIMULATION by S. V. Leonard, P. T. Golley, 10 April 1963, Memo No. M-ASTR-N-314.

13. Haeussermann, Walter and Hans Kennel, A SATELLITE MOTION SIMULATOR, Astronautics, 5, No. 12, December 1960.

14. Otto, Edward W., A LOW-TORQUE SUPPORT FOR LOW THRUST MEASUREMENT AND ATTITUDE CONTROL TESTING, High-Vacuum Technology, Testing, and Measurement Meeting, August 1966, pp. 95 - 100, N66-35906.

15. Imgram, D. A., R. R. Ziemer, E. Stern, DESIGN AND DYNAMIC TESTING OF AND ULTRAHIGH ACCURACY SATELLITE STABILIZATION AND CONTROL SYSTEM FOR THE ORBITING ASTRONOMICAL OBSERVATORY.

16. Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 14 February 1967.

17. Muench, W. K., DESIGN AND PERFORMANCE OF A LARGE AIR BEARING SPACECRAFT ATTITUDE SIMULATOR, Society of Automotive Engineers and American Society of Mechanical Engineers, Air Transport and Space Meeting, 27 - 30 April 1964, Paper 866G, A64-20849.

18. California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California, GAS LUBRICATION IN INSTRUMENTS AND CONTROL DEVICES by J. H. Laub, November 1960, AD 248 640.

19. The Boeing Company, Space Division, Seattle, Washington, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 24 February 1967.

LITERATURE CITED (Concluded)

20. The Bendix Corporation, Eclipse-Pioneer Division, Teterboro, New Jersey, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 24 February 1967.

21. Atlantic Research Corporation, Missile Systems Division, Costa Mesa, California, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 23 February 1967.

22. LTV Aerospace Corporation, Missile and Space Division, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 2 March 1967.

23. Avco Corporation, Avco Space Systems Division, Wilmington, Massachusetts, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 1 March 1967.

24. General Electric Company, Defense Electronics Division, Binghamton, New York, ATTITUDE MOTION SIMULATION FACILITY DATA received from company, 30 March 1967.

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Redstone Scientific Information Center Research and Development Directorate U. S. Army Missile Command ~~Redstone Arsenal, Alabama 35809~~	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

FACILITIES FOR SIMULATING ATTITUDE MOTION OF SPACECRAFT

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

Herbert H. Hoop

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1967	48	24

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) RSIC-679
b. PROJECT NO. N/A	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	AD

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Redstone Scientific Information Center Research and Development Directorate U. S. Army Missile Command ~~Redstone Arsenal, Alabama 35809~~

13. ABSTRACT

This report describes facilities using gas bearings in attitude motion simulators for the development of spacecraft attitude control systems. Typical facility information includes discussions on test chamber, bearing, platform, power requirements, balance consideration, testing procedure, attitude reference sources, sensors, and data transmission. Facilities at twelve Government and industrial organizations are discussed.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Attitude Motion Simulation						
Gas Bearings						
Air Bearings						
Spacecraft Attitude Control						
Attitude Control						
Simulator Balancing						